PROGRESS REPORT
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STUDIES OF INTERSTELLAR PICKUP IONS IN THE SOLAR WIND

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Abstract

The work under this grant involves studies of the interaction of interstellar pickup ions with the solar wind, with the goal of a comprehensive model of the particle distributions and wave intensities to be expected throughout the heliosphere, as well as the interactions of those distributions with the solar wind termination shock.

In the past year, we have completed a number of projects, including observations and modeling of the effects of a large scattering mean free path on the pickup He^+ seen at AMPTE, an analytical model of anisotropic pickup ions in a steady radial magnetic field, and a derivation of a reduced solar wind Mach number due to increased estimates on the inflowing hydrogen density allowing for a weak termination shock.

In the next year, we plan to investigate in more detail the correspondence between our models of anisotropic pickup ions and the data on spectra, variations, and proton-He^+ correlation provided by AMPTE, Ulysses, and our instrument on SOHO. We will model the time-dependent pickup ion density resulting from finite periods of radial magnetic field. We will also incorporate the effects of a large mean free path into our analysis of the He^+ focusing cone, leading to more accurate parameter values for the interstellar helium gas.

This progress report also includes a discussion of our Space Physics Educational Outreach activities in the past year and plans for the next year.

Introduction

We are pleased to report that our work on pickup ions under NASA grant NAGW - 2579 is doing extremely well. Our ultimate goal in this work is to model the interactions between the interstellar pickup ions and the solar wind in order to predict the properties of the distant solar wind and termination shock, to understand more completely the fundamental processes by which these particles interact with the solar wind, to pinpoint the source of the anomalous cosmic rays, and to provide information on the very local interstellar medium. To this end, we are combining theoretical plasma physics calculations with investigations and modeling of pickup ion data from AMPTE and other spacecraft. Our ongoing efforts have resulted in the publication or submission of 13 papers and the presentation of 9 invited talks and 6 contributed talks in the past year. In this report we will discuss the progress which has been made in 1996 and our anticipated projects for the coming year.

The funds requested from NASA for our third year are $75,000, identical to the award for our second year, on the assumption that the new grant from GSFC was initiated to match the otherwise continuing grant from Headquarters.

Work This Year

Anisotropic Pickup Ion Distributions. As anticipated in our last progress report, much of our work this year has focused on the surprising discovery of strong anisotropies in the distribution of interstellar pickup ions.[1] We have found clear indications of similar effects in our AMPTE SULEICA pickup He^+ data during times when the average interplanetary magnetic field (IMF) is oriented near to the radial direction. The SULEICA instrument can only detect the portion of the pickup ion distribution moving faster than the bulk solar wind (in the spacecraft frame), and we find that this anti-sunward portion of the distribution is strongly depleted during times of radial IMF. Our interpretation of these observations is that the new ions, appearing in the sunward, low-speed region of phase space when the IMF is radial, have considerably more difficulty pitch-angle scattering into the observable anti-sunward region than indicated by the theoretical assumptions of the last 20 years. The fact that these He^+ measurements can be made with time resolution of less than 15 minutes allows for the strong identification of these depletions with periods of radial field. In contrast, the pickup proton measurements at Ulysses are usually accumulated over periods of 10 hours or more, and the anisotropy measurement[1] was obtained over a one-month period.

This relatively high time resolution also allowed us to observe the effects of IMF changes from near-radial to orientations nearly perpendicular to the solar wind flow. In such cases, the ions piling up in the sunward region of phase space during radial field are suddenly swept up by the perpendicular field, resulting in a measurable ion density in the anti-sunward region which exceeds the nominal pickup ion density. This connection between the detailed time-dependence of the IMF angle and the anti-sunward pickup ion density will be common to all pickup ions and probably contains the explanation for the observed high variability of this density and the correlation between the pickup protons and helium.[2] These AMPTE observations were modeled by a simple two-stream pickup ion distribution, and a mean free path for pitch-angle scattering on the order of 1 AU was derived. This work has been submitted for publication in *Journal of Geophysical Research*.

We have also constructed a more detailed model of the anisotropic pickup ion distribution in a steady, radial IMF. First, we derived a transport equation appropriate for pickup ions moving in the solar wind at speeds comparable to the solar wind speed. Previous models of the distribution[1] used a cosmic ray convection-diffusion equation which is not valid for these particles. Then we applied a "hemispherical" assumption, taking the ions to pitch-angle scatter efficiently to isotropy within each hemisphere with respect to the magnetic field, but encountering substantial difficulty scattering across $\mu = 0$ from one hemisphere to the other. This hemispherical model is an extension of the two-stream formalism with the advantage that energy information is retained and model spectra can be produced. Finally, we obtained an analytical solution for the pickup ion distribution in each hemisphere as a function of position and energy. This work will appear in the *Journal for Geophysical Research.*

Pickup Proton Effects on the Distant Solar Wind. A recent analysis of anomalous cosmic ray gradients and spectra[3] has determined that the solar wind termination shock during 1994 was located at 85 ± 5 AU with a compression ratio of 2.63 ± 0.14. Such a weak shock is difficult to reconcile with standard models of the solar wind and inflowing interstellar hydrogen. In a paper submitted to *Geophysical Research Letters*, we pointed out that new information on two separate techniques for estimating the amount of hydrogen flowing into the heliosphere has lead to upward revisions of these estimates. We showed that the higher pickup proton densities which result are sufficient to slow and heat the solar wind to the extent that a standing shock near 85 AU would have a compression ratio in the predicted range.

Space Physics Educational Outreach Activities. We have initiated the work proposed for these supplemental funds. A show for the Christa McAuliffe Planetarium featuring a visualization of the flow of interstellar gas into the heliosphere is in the planning stages. Parts of the show will be based on existing sequences of the Planetarium's Hubble Space Telescope presentation. We will add visual effects depicting the interstellar gas flowing across the sky as though one could see it. A computer file containing the relevant data to be used by the Planetarium's Digistar program is currently being prepared by a student majoring in science education. In addition, a physics undergraduate is working on an animation of the pickup process for the Planetarium show and for display on the World Wide Web. A preliminary version is under review by Möbius, our Institute's graphics designer, and a video animation consultant.

Other Activities. M. A. Lee joined R. Lallement and R. von Steiger to edit the proceedings of the first International Space Science Institute Workshop, entitled *The Heliosphere in the Local Interstellar Medium* to be published by Kluwer. Lee also joined J. Lockwood and F. B. McDonald to organize the W. R. Webber Symposium on Cosmic Rays in the Heliosphere and Galaxy, held in Durham in October 1996.

Work Next Year

Comparison of Hemispherical Model with Pickup Helium Observations. Our hemispherical model of anisotropic pickup ions makes specific predictions on the structure of the anti-sunward particle distribution in a radial IMF, as a function of the pitch-angle scattering mean free path. Using our detailed model for neutral helium in the heliosphere,[4] we will check these predictions with the pickup He^+ data from the AMPTE spacecraft and the new data from our instrument on SOHO. The high time resolution of the pickup He^+ data,

mentioned above, will allow us to investigate possible variations of the mean free path with solar wind conditions. Furthermore, the mean free path for He^+ may well be different than that for protons, since the resonance gap around $\mu = 0$ depends on the mass/charge of the particle. It will be interesting to see if species-dependent effects are evident, and if so, whether they conform to our expectations from the resonant cyclotron interaction.

Analysis of Density Variations and the Proton-Helium Correlation. The depletions and enhancements of pickup ion density observed at AMPTE as a function of IMF angle are the likely cause of the unexpected variability of the anti-sunward pickup ion density, as well as the possible explanation of the peculiar correlation between the pickup proton and He^+ density seen at Ulysses.[2,5] We are collaborating with J. Giacalone of the University of Arizona to model the observed dependence of the density on IMF angle in an effort to compare this theoretical possibility with the Ulysses data.

Time-Dependent Model of Pickup Ion Enhancements. A rigorous description of the enhancement in anti-sunward pickup He^+ density seen at AMPTE when a quasi-perpendicular IMF follows a period of quasi-radial IMF requires a solution of the time-dependent transport equation for anisotropic particles. We will construct a two-stream solution of this time-dependent problem to model these enhancements.

Improved Interstellar Helium Model. A long pitch-angle scattering mean free path for pickup ions will have important consequences for models of the inflowing neutral gas. Inflowing densities can be more accurately determined by restricting the analysis to quasi-perpendicular conditions, and this has been done for both hydrogen[6] and helium.[4] However, the velocity and temperature of the inflowing helium are obtained from the observed structure of the focusing cone, and the spatial transport of the pickup ions implied by the long mean free path will affect that structure. In collaboration with D. Rucinski of the Polish Academy of Sciences, we will incorporate these effects into our detailed model of the inflowing interstellar helium.

Space Physics Educational Outreach Activities. In the next year, we will complete our initial Planetarium presentation on the inflowing interstellar gas and our animation of the pickup process for the Planetarium and the World Wide Web. In addition, we will begin work on new animations for display on the World Wide Web of the interstellar gas as well as of the principles behind our instrumentation to measure this gas. We will also conduct a "design review" of our outreach projects with local high school teachers and students to provide useful information on future connections with this target audience.

References

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Publications in the Past Year

Feldman, W. C., J. L. Phillips, J. T. Gosling and P. A. Isenberg, Electron impact ionization rates for interstellar neutral H and He atoms near interplanetary shocks: Ulysses observations, in *Solar Wind 8*, ed. by D. Winterhalter, D. J. McComas, J. L. Phillips, and N. Murphy, AIP, New York, in press, 1996.

Isenberg, P. A., Effects of spatial transport and ambient wave intensity on the generation of MHD waves by interstellar pickup protons, in *Solar Wind 8*, ed. by D. Winterhalter, D. J. McComas, J. L. Phillips, and N. Murphy, AIP, New York, in press, 1996.

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Rucinski, D., A. C. Cummings, G. Gloeckler, A. J. Lazarus, E. Möbius, and M. Witte, Ionization processes in the heliosphere - Rates and methods of their determination, *Space Sci. Rev.*, in press, 1996.

Talks in the Past Year

Invited:

Isenberg, P. A., Interstellar pickup ions: Theory and observations, IAGA General Assembly, Uppsala, Sweden, August 1997.

Lee, M. A., Ion thermalization and wave excitation downstream of the quasi-perpendicular bow shock, Seminar, Space Research Centre, Warsaw, Poland, January 1996.

Lee, M. A., Workshop summary, Ulysses Workshop on CIR's, Elmau Castle, Germany, March 1996.

Lee, M. A., Acceleration of the corotating ion events, AGU Spring Meeting, Baltimore, May 1996.

Lee, M. A., Ion acceleration at corotating interaction regions in the solar wind, Seminar, MPI Aeronomie, Lindau, Germany, July 1996.

Lee, M. A., CIR's and acceleration of energetic ions, SOHO CELIAS Scientific Workshop, Kloster Seeon, Germany, September 1996.

Lee, M. A., Energetic ions and the solar wind termination shock, AGU Fall Meeting, San Francisco, December 1996.

Lee, M. A., Particle acceleration in interplanetary space, ACE Science Workshop, Caltech, Pasadena, CA, January 1997.

Lee, M. A., Injection at the termination shock, IAGA General Assembly, Uppsala, Sweden, August 1997.

Contributed:

Hilchenbach, M., D. Hovestadt, B. Klecker, and E. Möbius, Lunar pickup ions near the lunar surface as deduced from observations of an Earth-orbiting satellite, International Moon Workshop, Berlin, Germany, February 1996.

Isenberg, P. A., Anisotropy and spatial transport of interstellar pickup ions - Two stream analysis, AGU Spring Meeting, Baltimore, May 1996.

Isenberg, P. A., A weaker solar wind termination shock, Symposium on Cosmic Rays in the Heliosphere and Galaxy, Durham, October 1996.

Isenberg, P. A., and M. A. Lee, Consequences of the hemispherical model on fluctuations of interstellar pickup ions, AGU Fall Meeting, San Francisco, December 1996.

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